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Preliminary Review of Retrieval Issues for a High-Level Nuclear Waste Repository in Salt

Technical Report

November 1987

Lawrence A. Smith

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ABSTRACT

This document highlights topics related to the retrieval of nuclear waste from a mined geologic repository in salt. Retrieval is an event that, although it is not expected, must be planned for. Major programmatic documents and Federal regulations require that the waste should be retrievable. It is therefore an important design consideration that the option exists to retrieve waste in the unlikely event retrieval is needed. There are several broad issues involved in a repository in salt that have significant implications to retrieval systems. Among these are high temperatures that can affect mining equipment operation and personnel safety; the viscoplastic behavior of salt that results in room closure and increased potential for unstable openings; and nuclear issues such as radiation and contamination, criticality, and accountability and safeguards.

FOREWORD

The National Waste Terminal Storage Program was established in 1976 by the U.S. Department of Energy's predecessor, the Energy Research and Development Administration. In September 1983, this program became the Civilian Radioactive Waste Management (CRWM) Program. Its purpose is to develop technology and provide facilities for safe, environmentally acceptable, permanent disposal of high-level waste (HLW). HLW includes wastes from both commercial and defense sources, such as spent (used) fuel from nuclear power reactors, accumulations of wastes from production of nuclear weapons, and solidified wastes from fuel reprocessing.

The information in this report pertains to the engineering studies of the Salt Repository Project of the Office of Geologic Repositories in the CRWM Program.

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1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this document is to highlight topics related to the retrieval of nuclear waste from a mined geologic repository in salt. It may also serve as an introduction to retrieval for people who are new to the subject. It does not state a position on retrieval and in no way should be construed as supporting any position on retrieval. The document catalogs ideas raised about retrieval, but it is not intended to draw final conclusions about the validity of these ideas. This work is a very preliminary step in initiating a plan to develop a position on retrieval.

1.2 SCOPE

Current or reasonably available technology will be taken as the basis of this study. Whenever possible, existing equipment capabilities and limits will be referenced. If necessary, some limited extrapolation of current design capabilities will be allowed, but no dramatic improvements in performance will be assumed.

The intention is to establish preliminary functional requirements based on the programmatic, regulatory, and technical guidelines; to review planned approaches to retrieval; and to present key issues that control retrieval options. Design features and equipment requirements of a salt repository will be reviewed in light of the functional requirements.

1.3 TECHNICAL APPROACH

Programmatic guidelines and Federal regulations are first reviewed to establish a basis for this study of retrievability. These major documents set the overall context for discussions of retrieval. The concept of scenarios as a basis for analysis of retrieval methods is then introduced. Several scenarios are developed to describe retrieval conditions and focus on more detailed retrieval analysis. The scenarios will not predict all conditions but will be selected to include the range of possible conditions so that there is confidence that any conditions that arise can be met.

After the basis is established, several key challenges in retrieval are discussed. These are items that are broad in scope so that they touch on many of the retrieval steps. They are discussed at this point because attempting to discuss them in the chapter describing retrieval operations would result in the repetition of similar material in several sections. This discussion also provides an introduction to the consideration of specific retrieval operations by describing some of the key challenges in designing retrieval systems.

The retrieval operations are then outlined and presented as unit operations. Functional requirements, possible approaches, and major concerns are discussed for each operation.

1.4 PREVIOUS WORK

There has been considerable prior analysis of the retrieval issue. The results of this earlier analysis were used in the preparation of this document. Prior work within the U.S. Department of Energy's Salt Repository Project is described in

- National Waste Terminal Storage Repository No. 1 (Stearns-Roger Engineering Company, 1979)
- A National Waste Terminal Storage Repository in a Bedded Salt Formation for Spent Unreprocessed Fuel (Kaiser Engineers, 1978)
- Retrieval Options Study (Kaiser Engineers, Inc., 1980)
- Preliminary Assessment of a Technical Basis for Establishing a Retrievability Period (Wilems et al., 1980a)
- Retrievability: Technical Considerations (Wilems et al., 1980b).

In addition, the U.S. Nuclear Regulatory Commission has studied retrieval as reported in

- Assessment of Retrieval Alternatives for the Geologic Disposal of Nuclear Waste (Kendorski et al., 1984).

2.0 BASIS

2.1 PROGRAMMATIC AND REGULATORY REQUIREMENTS

The requirement to not preclude the ability to retrieve nuclear waste flows down from the highest level project documents including the Nuclear Waste Policy Act of 1982, 10 CFR Part 60, 10 CFR Part 960, and 40 CFR Part 191. These documents have been reviewed to establish the overall programmatic and regulatory framework for retrieval. Rather than summarizing the documents, the applicable sections will be quoted. This is done to avoid any misinterpretation due to bias or misunderstanding on the part of the author.

2.1.1 Nuclear Waste Policy Act of 1982

Sec. 2(18)

> The term "repository" means any system licensed by the Commission that is intended to be used for, or may be used for, the permanent deep geologic disposal of high-level radioactive waste and spent nuclear fuel, whether or not such system is designed to permit the recovery, for a limited period during initial operation, of any materials placed in such system. Such term includes both surface and subsurface areas at which high-level radioactive waste and spent nuclear fuel handling activities are conducted.

Sec. 121(b)(1)(B)

> Such criteria shall provide for the use of a system of multiple barriers in the design of the repository and shall include such restrictions on the retrievability of the solidified high-level radioactive waste and spent fuel emplaced in the repository as the Commission deems appropriate.

Sec. 122

> Notwithstanding any other provision of this subtitle, any repository constructed on a site approved under this subtitle shall be designed and constructed to permit the retrieval of any spent nuclear fuel placed in such repository, during an appropriate period of operation of the facility, for any reason pertaining to the public health and safety, or the environment, or for the purpose of permitting the recovery of the economically valuable contents of such spent fuel. The Secretary shall specify the appropriate period of retrievability with respect to any repository at the time of design of such repository, and such aspect of such repository shall be subject to approval or disapproval by the Commission as part of the construction authorization process under subsections (b) through (d) of section 114.

2.1.2 10 CFR Part 960

10 CFR 960.2

"Retrieval" means the act of intentionally removing radioactive waste before repository closure from the underground location at which the waste had been previously emplaced for disposal.

10 CFR 960.5-2-9(c)(4)

Potential for such phenomena as thermally induced fracturing, the hydration and dehydration of mineral components, or other physical, chemical, or radiation-related phenomena that could lead to safety hazards or difficulty in retrieval during repository operation.

2.1.3 40 CFR Part 191

40 CFR 191(3)(b)(vi)

Recovery of most of the wastes must not be precluded for a reasonable period after disposal if unforeseen events require this in the future.

Comments on Issues Highlighted for Public Review,
Ability to Recover Wastes After Disposal

The proposed rule included an assurance requirement that recovery of these wastes be feasible for "a reasonable period of time" after disposal. The Agency specifically sought comment on whether this was a desirable provision, since it would rule out certain disposal concepts, such as deep-well injection of liquid wastes. The comments received were split about evenly between those who thought the provision should be retained and those who thought it was detrimental to the overall rule. Many of those who opposed the requirement argued that it would encourage designing a geologic repository to make retrieving waste relatively easy--which might compromise the isolation capabilities of the repository or which might encourage recovery of the waste to make use of some intrinsic value it might retain (the potential energy content of spent nuclear fuel, for example).

The intent of this provision was not to make recovery of waste easy or cheap, but merely possible in case some future discovery or insight made it clear that the wastes needed to be relocated. EPA reiterates the statement in the preamble to the proposal that <u>any</u> current concept for a mined geologic repository meets this requirement <u>without</u> any additional procedures or design features. For example, there is no intent to require that a repository shaft be kept open to allow future recovery. To meet this assurance requirement, it only need be technologically feasible (assuming current technology levels) to be able to mine the sealed repository and recover the waste--albeit at substantial cost and occupational risk. The Commission's requirements for multiple engineered barriers within a repository (10 CFR Part 60) adequately address any concerns about the feasibility of recovering wastes from a repository.

Therefore, this provision should not have any effect upon plans for mined geologic repositories. Rather, it is intended to call into question any other disposal concept that might not be so reversible--because the Agency believes that future generations should have options to correct any mistakes that this generation might unintentionally make. Almost all of the commenters agreed with the validity of this objective. Accordingly, the Agency has decided to retain this assurance requirement in the final rule as proposed.

40 CFR 191.02(k) and (l)

(k) "Storage" means retention of spent nuclear fuel or radioactive wastes with the intent and capability to readily retrieve such fuel or waste for subsequent use, processing, or disposal.

(l) "Disposal" means permanent isolation of spent nuclear fuel or radioactive waste from the accessible environment with no intent of recovery, whether or not such isolation permits the recovery of such fuel or waste. For example, disposal of waste in a mined geologic repository occurs when all of the shafts to the repository are backfilled and sealed.

40 CFR 191.14(f)

Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal.

2.1.4 <u>10 CFR Part 60</u>

10 CFR 60.2

"Retrieval" means the act of intentionally removing radioactive waste from the underground location at which the waste had been previously emplaced for disposal.

10 CFR 60.21(c)

The Safety Analysis Report shall include:....(12). A description of plans for retrieval and alternate storage of the radioactive wastes should the geologic repository prove to be unsuitable for disposal of radioactive wastes.

10 CFR 60.102(d)

There are several stages in the licensing process. The <u>site characterization</u> stage, though begun before submission of a license application, may result in consequences requiring evaluation in the license review. The construction stage would follow, after issuance of a construction authorization. A period of operations follows the issuance of a license by the Commission. The period of operations includes the time during which emplacement of wastes occurs; any subsequent period before permanent closure during which the emplaced wastes are retrievable; and permanent closure, which includes sealing of shafts. Permanent closure represents the end of active human intervention with respect to the engineered barrier system.

10 CFR 60.111(b)

(1) The geologic repository operations area shall be designed to preserve the option of waste retrieval throughout the period during which wastes are being emplaced and, thereafter, until the completion of a performance confirmation program and Commission review of the information obtained from such a program. To satisfy this objective, the geologic repository operations area shall be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are inititated, unless a different time period is approved or specified by the Commission. This different time period may be established on a case-by-case basis consistent with the emplacement schedule and the planned performance confirmation program.

(2) This requirement shall not preclude decisions by the Commission to allow backfilling part or all of, or permanent closure of, the geologic repository operations area prior to the end of the period of design for retrievability.

(3) For purposes of this paragraph, a reasonable schedule for retrieval is one that would permit retrieval in about the same time as that devoted to construction of the geologic repository operations area and the emplacement of wastes.

10 CFR 60.132(a)

Surface facilities in the geologic repository operations area shall be designed to allow safe handling and storage of wastes at the geologic repository operations area, whether these wastes are on the surface before emplacement or as a result of retrieval from the underground facility.

10 CFR 60.133

(c) Retrieval of waste. The underground facility shall be designed to permit retrieval of waste in accordance with the performance objectives of § 60.111.

(e) Underground openings. (1) Openings in the underground facility shall be designed so that operations can be carried out safely and the retrievability option maintained.

10 CFR 60.140 to 143, Performance Confirmation Program

Retrievability is not mentioned.

10 CFR 60, Statements of Consideration (10 CFR 60, SC, p. 10)

Retrievability

The purpose of this requirement was to implement in a practical manner the licensing procedures which provided for temporal separation of the emplacement decision from the permanent closure decision. Since the period of emplacement would be lengthy and since the knowledge of expected repository performance could be substantially increased through a carefully planned program of testing, the Commission wished to base its decision to permanently close on such information. The only way it could envision this was to insist that ability to retrieve--retrievability--be incorporated into the design of the geologic repository.

The proposed rule would have required in effect that the repository design be such as to permit retrieval of waste packages for a period of up to 110 years (30 years for emplacement, 50 years to confirm performance, 30 years to retrieve). The Commission solicited comment, noting that it would not want to approve construction of a design that would unnecessarily foreclose options for future decision makers, but that it was concerned that retrievability requirements not unnecessarily complicate or dominate repository design.

While the benefits of retaining the option of retrieval were recognized, the length of the proposed requirement, in the opinion of several commenters, was excessive. In their view, the Commission had given inadequate consideration to the additional costs of design, construction, and operations implied in the original proposal; however, no new cost or design information was presented by the commenters.

The Commission adheres to its original position that retrievability is an important design consideration. However, in response to the concerns expressed, the Commission has decided to rephrase the requirement in functional terms. The final rule thus specifies that the design shall keep open the option of waste retrieval throughout the period during which the wastes are being emplaced and, thereafter, until the completion of a performance confirmation program and Commission review of the information obtained from such a program. By that time, significant uncertainties will have been resolved, thereby providing greater assurance that the performance objective will be met. In particular, the performance confirmation program can provide indications whether engineered barriers are performing as predicted and whether the geologic and hydrologic response to excavation and waste emplacement is consistent with the models and tests used in the Commission's earlier evaluations. While the commission has provisionally specified that the design should allow retrieval to be undertaken at any time within 50 years after commencement of emplacement operations, this feature is explicitly subject to modification in the light of the planned emplacement schedule and confirmation program for the particular geologic repository.

Some commenters suggested that the technical criteria specify the conditions that would require retrieval operations to be initiated. Such provisions would not belong in Subpart E, which is concerned with siting and design. Nor are they needed elsewhere. In the Commission's view, it is clear that retrieval could be required at any time after emplacement and prior to permanent closure if the Commission no longer had reasonable assurance that the overall system performance objective would be met. This situation could exist for a variety of reasons and the Commission believes that it should retain the flexibility to take into account all relevant factors and that it would be imprudent to limit the Commission's discretion by specifying in advance the particular circumstances that would make it necessary to retrieve wastes. It should be noted that DOE may elect to maintain a retrievability capability for a longer period that the Commission has specified, so as to facilitate recovery of the economically valuable contents of the emplaced materials (especially spent fuel). So long as the other provisions of the rule are satisfied this would not be prohibited. This consideration, however, plays no role in the Commission's requirement pertaining to retrievability. The Commission's purpose is to protect public health and safety in the event the site or design proves unsuitable. The provision is not intended to facilitate recovery for resource value.

The Commission has also included a specific provision clarifying its prior intention that the retrievability design features do not preclude decisions allowing earlier backfilling or permanent closure. A related clarifying change has been the incorporation of a definition of "retrieval." This definition indicates that the requirement of retrievability does not imply ready or easy access to emplaced wastes at all times prior to permanent closure. Rather, the Commission recognizes that any actual retrieval operation would be an unusual event and may be an involved and expensive operation. The idea is that it should not be made impossible or impractical to retrieve the wastes if such retrieval turns out to be necessary to protect the public health and safety. DOE may elect to backfill parts of the repository with the intent that the wastes emplaced there will never again be disturbed; this is acceptable so long as the waste retrieval option is preserved.

The Commission has thus retained the essential elements of the retrievability design feature, but has provided greater flexibility in its application. The Commission recognizes that retrievability implies additional costs--more, perhaps, for some media and designs than for others--yet it believes this is an acceptable and necessary price to pay if it enables the Commission to determine with reasonable assurance, prior to an irrevocable act of closure, that the EPA standard will be satisfied.

Section 60.111 Performance of the geologic repository operations area through permanent closure [§ 60.111(a)] (10 CFR 60, SC, p. 21)

The provisions of § 60.111(a) dealing with radiation protection and releases of radioactive material for the period through permanent closure of the underground facility are unchanged in substance from the proposed rule. The paragraph has been renumbered and some editorial changes have been made.

The provisions of § 60.111(b) dealing with retrievability of waste have been modified to link the period of retrievability more closely to the performance confirmation program and to allow the Commission to modify the retrievability period on a case-by-case basis based on the waste emplacement schedule and the planned performance confirmation program. The final rule also specifies that the period of retrievability begin at the initiation of waste emplacement rather than after waste emplacement is complete. Finally, the final rule explicity states that backfilling of portions of the underground facility is not precluded, provided the retrievability option is maintained, and that the Commission may decide to allow permanent closure of the underground facility prior to the end of the designed retrievability period. While these provisions were discussed in the supporting information, they were not explicitly stated in the proposed rule. Also see Retrievability, above.

2.2 SCENARIO DEVELOPMENT

A number of conditions, all highly unlikely, could lead to a decision to retrieve emplaced nuclear waste. These conditions would be the basis for scenario development, and they include the following:

1. Natural events and processes: the occurrence of totally new, unknown, and unexpected natural phenomena in the environment of an operating repository could render it unusable.

2. Geologic and hydrologic responses to excavation and waste emplacement: the design of the repository will be based on data obtained from sampling and testing and on accepted thermal, mechanical, and hydrologic models. Designs will incorporate margins of safety to accommodate reasonable assumptions of inaccuracies in such design bases. Nevertheless, abandonment of the repository, or a portion of the repository, could conceivably be dictated if performance characteristics or the occurrence of anomalous zones in the host rock indicate that the required degree of confidence in the predicted performance could, for some reason, no longer be provided.

3. Predicted waste package performance: postemplacement evaluations could indicate that certain waste packages have defects or that the engineered barrier design is not performing as predicted. Retrieval of some defective waste packages or of all emplaced waste could be dictated in this event.

4. Repository system operation: the final integrated system of the first repository could conceivably be judged not operable due to either an uncorrectable inadequacy of the design basis or small but chronic inadequacies that, with time, build to an intolerable level.

5. Economic resource recovery: the value of the fissile material may become sufficiently high to necessitate retrieval.

It is not possible to define a single set of conditions that will exist at the time of retrieval. The complexity of the repository design and the variety of potential causes for requiring retrieval preclude this. For example, the repository conditions attendant upon a retrieval for economic resource recovery would be different from the retrieval conditions resulting from an unexpected natural event. Also, it may not be possible to define all of the conditions a priori even if the driving events are known.

One method for establishing a design basis when exact conditions are not definable is a scenario-based design. This approach is frequently used in nuclear licensing accident analysis. The scenario must be plausible and self-consistent. The scenarios should be formed to bound a complete set of reasonable and defensible operating and design basis accident conditions. The scenarios should account for the full spectrum of possible retrieval events but may not detail all possible events.

Some factors that should be included in the scenario analysis are

- Timing of room backfill
- Emplacement mode
- Areal power density (packages per unit area)
- Repository condition
- Waste package condition
- Time of retrieval
- Reason for initiating retrieval.

A set of scenarios must eventually be developed that defines the conditions for the design of retrieval equipment. Some of the subjects that should be considered in developing the scenarios are discussed in the following sections. It should not be assumed that all of the subjects raised can be combined to form a worst case. Since retrieval may itself be a low probability event, there should be no need to combine it with a sequence of other low probabilty events. Many potential challenges to the retrieval system are raised in this document, and there is not a sufficient technical basis to dismiss them at this time. However, during scenario development it is probable that some of these concerns will be shown to be invalid.

3.0 RETRIEVAL TOPICS

This chapter will summarize topics that have effects on many aspects of retrieval in order to set a framework for the discussions of methods in Chapters 4 and 5. Included among these topics are thermal effects, ground control, and nuclear concerns.

3.1 THERMAL EFFECTS

A dominant fact that has broad implications for retrieval is that salt is a viscoplastic medium and the salt creep rate increases significantly with temperature. The plastic behavior of salt combined with the elevated temperatures can have significant effects on the retrieval operation.

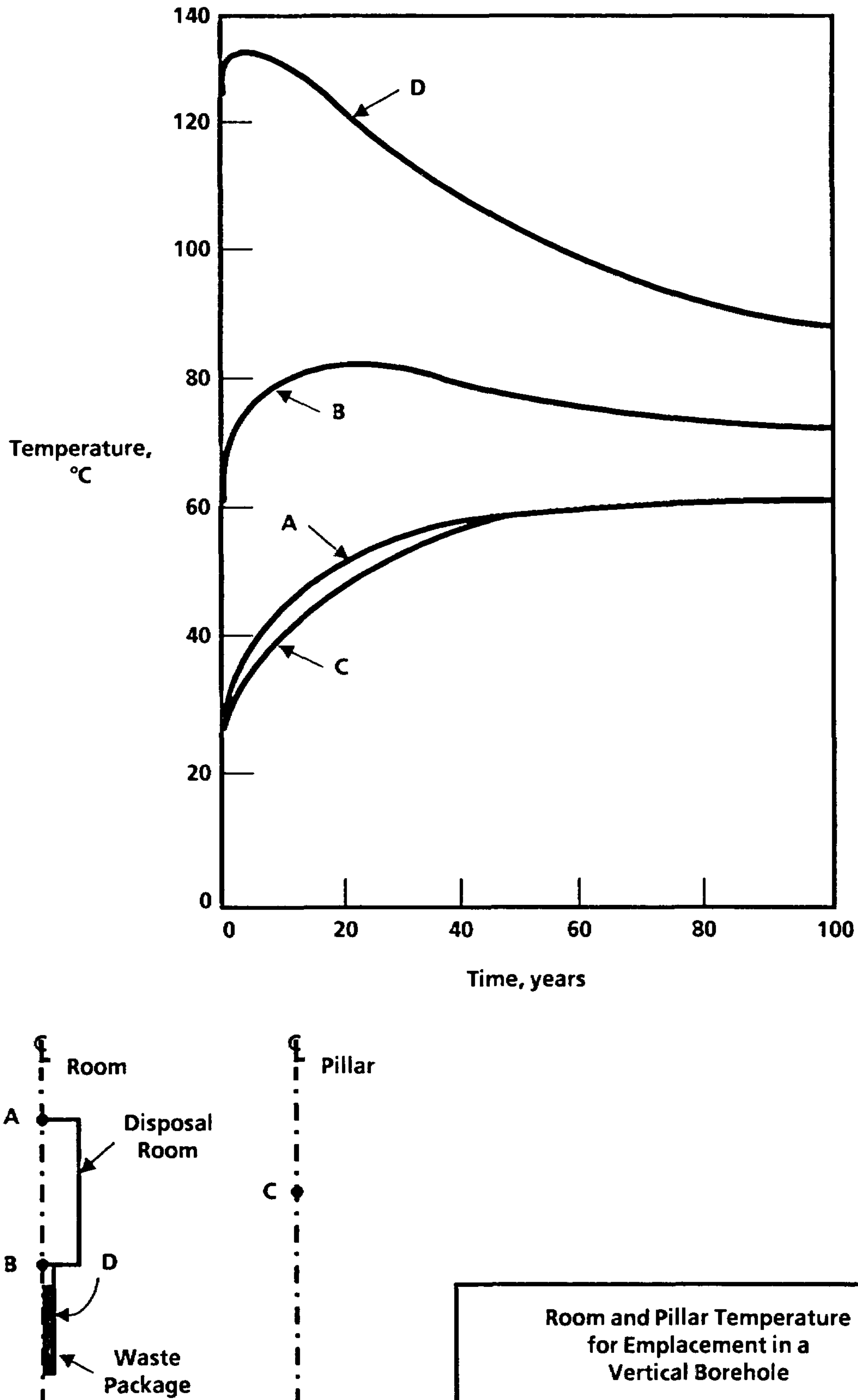
Some of these effects are as follows:

- Closure of the storage hole around the package, locking it firmly in place
- Creep closure of the main passages and emplacement rooms
- Potential weakening of the emplacement room walls, roof, and floor.

Other important issues are brine migration and the nuclear aspects of the processes involved in package handling.

3.1.1 Temperature Profiles

This section describes the results of a thermal analysis done to estimate temperatures in the vicinity of a waste package containing 12 consolidated pressurized-water reactor fuel elements (6,600 W heat output). The repository is modeled in three dimensions using HEATING5 (Turner et al., 1977). This program uses the finite-difference solution method to solve heat conduction problems. It calculates temperature throughout the repository as a function of time. To simplify the repository model, adiabatic boundaries are taken on all sides. Above and below, the boundaries are placed about 750 m (2,460 ft) from the ends of the container. These levels are chosen to minimize the effect of the boundaries during the 1,000-year transient calculation. Vertical planes of symmetry around the waste package form the other four adiabatic boundaries. Adiabatic boundaries around the waste package represent a physical situation where the modeled package is surrounded by other packages of identical geometry, power, and properties. The use of adiabatic boundaries will overstate the repository temperatures because it assumes that all packages are present at time zero and that there is no heat loss from the system to the surroundings. The temperature results are shown in Figure 3-1.



Room and Pillar Temperature for Emplacement in a Vertical Borehole

Figure 3-1

3.1.2 Working Environment Concerns

Elevated temperatures will require some modifications to equipment, but the major concern is worker safety, efficiency, and comfort. Due to the heat generation capability of the nuclear waste, the salt temperatures in the repository will be higher than temperatures typically encountered in mining practice. Mining in rock at a temperature less than 30°C (86°F) is not a problem. Operating in rock temperature up to 40°C (104°F) is frequently done. There is some experience with mining rock at temperatures up to 90°C (194°F) (Hiramatsu et al., 1979). However, providing a tolerable working environment for personnel at these temperatures will present challenges.

Temperatures in the range of 60 to 80°C (140 to 176°F) may be encountered throughout much of the repository within a few years after emplacement. Near the waste package, the temperatures may be above 100°C (212°F). Therefore, the retrieval operation can be expected to encounter difficulties due to elevated temperatures.

3.1.3 Creep Closure

The design of underground openings in salt must consider the creep behavior of the evaporite material. Creep is the slow, yet continuous deformation of a material such as occurs in glacier ice. In underground salt mines, openings have been completely closed by creep deformation (Baar, 1977). Factors that contribute to the rate of creep experienced in a mine include not only the salt composition and the geologic and structural conditions of the rock body, but also mining considerations such as the depth to excavation and the extraction ratio.

Creep movement is driven by the differential stress state applied to the rock. In an underground environment, the premining stress state that has achieved equilibrium over geologic time is perturbed by the excavation of openings. In a rock body, the perturbation causes a reduction in stresses in the radial direction, together with a modification of the stresses in other directions. The differential stresses cause salt rocks to deform toward the excavation. This movement is termed "stress relief creep" (Baar, 1977) because it is primarily promoted by the reduction in stress in the radial direction. The creep movements probably promote relaxation in the rock and consequent stress changes over time.

However, the state of stress around an excavation in salt is difficult to establish definitively. Theoretical evaluations are at present inadequate, because a proper constitutive equation giving the time-dependent relationships for stress and strain for salt has not been defined. Also, in situ stress measurements have proven unreliable, since salt can flow about the measuring device. However, Baar (1977) indicates that reliable measurements of normalized or spherical stress may be obtained in a borehole by using the United States Bureau of Mines cylindrical copper cells.

The difficulties in defining the stress state around an opening in salt have meant that predictions of creep closure are suspect. Since the retrieval of waste packages from an underground repository in salt will probably require mining through rock material at elevated temperatures, prediction of the rate of closure of openings will be a factor in considering retrieval operations. This is especially significant given the influence of temperature on creep rates for salt.

Studies of salt creep have found that creep rates are determined primarily by the salt material properties, the applied load, and the temperature. Increases in salt temperature have been found to dramatically increase creep rates. According to laboratory tests performed in conjunction with Project Salt Vault (Bradshaw and McClain, 1971) the effect of temperature on creep rates can be described by

$$(E_2/E_1) \propto (T_2/T_1)^{9.5} \tag{3-1}$$

where

E_1 = initial creep rate, in/in-hr
E_2 = creep rate at second temperature, in/in-hr
T_1 = initial temperature, K
T_2 = second temperature, K

Equation 3-1 implies that if repository temperatures increased by 55°C (100°F) (from 28°C [83°F], the expected ambient rock temperature in a repository in salt, to 83°C [183°F], a reasonable rock temperature during the retrieval period), and if everything else remained constant, then creep rate would increase fivefold. It must be emphasized, however, that Equation 3-1 is based on laboratory testing of salt from one location and was not confirmed by in situ testing. Other tests conducted during Project Salt Vault also found that thermal stresses caused by the emplacement of a heat source increased creep rates as much as tenfold even before the temperature of the salt mass had risen appreciably (Bradshaw and McClain, 1971).

The creep rates expected in a repository are of critical importance to repository design and retrieval. Although several "constitutive equations" for salt creep have been derived from laboratory data, they do not correlate very well when used in computer simulations of repository-scale rock behavior (Tillerson and Dawson, 1980). Moreover, the experience of Canadian deep potash mines (about 914 to 1,219 m [3,000 to 4,000 ft]) indicates that laboratory creep testing results may need further validation for application to mine design (Mraz, 1973; Baar, 1977). There is a major need for large-scale, long duration, in situ creep testing before creep predictions may be used with confidence in the design of a repository.

Salt creep affects retrieval in three distinct areas:

- Very near field - closure of the storage hole around the waste package
- Near field - horizontal and vertical closure of the storage room
- Intermediate field - closure of the main entries.

The effect of thermal load from nuclear waste will be to increase the closure rates experienced in each of the above three areas. The immediate effect of waste emplacement will be the imparting of thermal stresses. Once the salt temperature has increased and is nearly constant, the importance of thermal stresses will be lessened. However, the high temperature conditions will result in greatly increased creep rates.

The potential effects of creep on different repository and retrieval functions over the field of the repository are summarized in Table 3-1 and discussed in more detail in the following paragraphs.

3.1.3.1 Very-Near-Field Effects

The creep of the salt around the storage hole is expected to close any annulus and completely encase the waste package in salt before the end of the retrieval period. This may complicate retrieval because the waste package would be locked into the salt mass.

Another very-near-field thermal effect may be displacement of the canisters due to floor heave or buckling (Coyle and Kalia, 1985). Floor movements may be very substantial during the retrieval period, making an accurate waste package locating device necessary for retrieval.

3.1.3.2 Near-Field Effects

The effects of creep on storage rooms will differ according to whether the rooms are backfilled immediately after waste emplacement or left open and ventilated.

If the rooms are backfilled, creep occurring during the retrieval period will gradually compress the backfill. The choice of the remining system at the time of retrieval may be affected by backfill conditions such as the degree of backfill consolidation.

If the storage rooms are left open and ventilated during postemplacement, the salt temperature rise will not be as great as if the rooms were backfilled. Thermal stresses may, however, still be sufficient to contribute to increased creep rates. If excessive creep threatens to prevent access to the open rooms or causes subsidence and fracturing of overlying strata, it may be necessary to backfill the rooms before permanent closure. If only moderate creep occurs, then some minimal remining and floor trimming may be all that is required to maintain equipment access for retrieval. Attempting to keep the drifts open will also result in the need for larger ventilation air flow.

It would also be possible to leave the rooms open and maintain minimal air flow. In this case the temperatures would increase over the fully ventilated case but would be lower than in the backfilled case.

3.1.3.3 Intermediate-Field Effects

During the active life of the repository, including the specified retrieval period, it will be necessary to keep the main entries open for the movement of workers, material, and ventilating air. It is likely that some creep closures will occur in the main entries over this time period,

Table 3-1. Effects of Salt Creep on Retrieval

Location	Phenomena	Effects
Very Near Field (Storage Hole)	Closure of storage hole around waste package	Retrieval system must be designed to retrieve canisters encased in salt
	Displacement of waste package	Waste packages must be locatable
	Brine migration to waste package	Safety precautions must be taken against encountering pockets of fluid or air at high pressure or corroded canisters
Near Field (Room)	(Backfilled concept) recompaction of backfill	Degree of consolidation of backfill affects removal method
	(Backfilled concept) closure after remining	Large closure rates after remining may limit time available for retrieval
	Local instability of roof, pillars, and floor	Large closures may accelerate slabbing and buckling types of failures, making room less safe
	(Open concept) closure of open rooms	Excessive closure of the open rooms during the retrieval period would necessitate backfilling or a major maintenance program; moderate closures could result in remining or floor trimming
Intermediate Field (Main Entries)	Closure of main entries over long periods of operation with increasing temperatures over the active life of repository	Necessity for major maintenance including remining to keep main entries open

particularly if the temperature of the salt around the main entries is increasing. Even if the temperature of the salt pillars protecting the main entries does not increase appreciably, creep rates could still increase somewhat as the main entries may form an "abutment zone" carrying some of the overburden load of the more rapidly deforming, high temperature pillars in the waste storage area.

3.1.4 Brine Migration

The presence of a thermal gradient through the salt will cause brine inclusions to migrate up the temperature gradient toward the waste canisters (Olander et al., 1980). Brine migration occurs because the solubility of salt increases with temperature. Migration begins with the solutioning of salt by the included brine on the warmer face of the inclusion and the deposition of salt on the cooler side. The volume of the inclusion remains nearly constant, and movement of the inclusion toward the heat source results. (If, however, the temperature approaches the boiling point of the brine, a two-phase system (vapor/liquid) is formed; this two-phase system will tend to migrate down the temperature gradient and away from the canisters.)

The rate and quantity of brine inflow to a borehole containing a canister will be a function of

- Thermal load
- Temperature and thermal properties of the salt
- Solubility of the salt with temperature
- Salt purity
- Number and size of brine inclusions
- Amount of disturbance caused by installation of the borehole
- Geometry of the borehole
- Pressure.

The quantity of brine that might be present around a waste package is not well established. However, it is not possible to ensure that only minimal amounts of brine would be present. The brine around the package could be present as a pressurized liquid and possibly be at a temperature of over 100°C (212°F). When the brine pocket is broken open, the brine would flash boil to produce steam. This could present safety hazards to personnel or interfere with retrieval machine operation.

3.2 GROUND CONTROL

Ground control refers to the rock monitoring and rock support techniques adopted. There are three separate time phases of concern: during mine development and emplacement, during the backfilled period (if backfilling is used), and during re-entry and retrieval. It is important that the first two phases do not leave the salt in a condition that makes re-entry difficult. It is likely that some roof bolts will be needed at all sites during the development and emplacement phase. Upon backfilling, the salt will not be returned to its original density nor will it be possible to fill the drift completely. As a result, there will be incomplete support as the rooms close. This could result in slabbing.

3.3 NUCLEAR CONCERNS

Some challenges to retrieval arise directly from the nature of the nuclear waste. The waste emits penetrating radiation that limits the allowed contact time for workers and, in the event of a breached container, could cause contamination. The presence of fissile material, primarily uranium-235 and plutonium-238, allows in theory for nuclear criticality. Criticality is the condition of a sustaining nuclear chain reaction. Nuclear fuel should only be allowed to reach criticality under controlled conditions in a reactor core. Because of its value, fissile material must be carefully accounted for and safeguarded.

3.3.1 Radiation and Contamination

Retrieval of the package involves the potential for two different types of radiological hazards. These are direct radiation and radioactive contamination. An intact package is always a radiation source, but it must be breached to result in serious contamination. The chacteristics of, and control methods for, these two hazards are different.

The radiation hazard is a result of energy transport out of the canister, largely neutrons and gamma rays. The heavy steel container provides some shielding. However, the dose rate could be on the order of 200 rem/hr, too high to allow human contact for more than about a minute. If the canister is removed from the container, the dose rates will be several orders of magnitude higher.

Radiation hazards are controlled by combinations of three methods. These methods are increasing the amount of shielding, reducing the time of exposure, or increasing the distance from the operator to the source.

The contamination hazard is primarily a result of radioactive sources that are not contained. Problems with contamination will arise only in cases when breached canisters are retrieved. The contaminated material may be salt or brine that has picked up radionuclides or pockets of trapped air containing radioactive gases, primarily krypton-85. Contamination can be controlled by minimizing the production of dust, controlling the spread of dust, and controlling and filtering airflows.

Direct radiation from the package will be present even if the package is intact. Thus, radiation dose will be present and must be considered in the design of retrieval systems. There may be some minor contamination left on the container after fabrication, but for serious amounts of contamination to be present a waste package must have failed. Package failure, at least under normal circumstances, is not expected. The question of gaseous contamination, essentially krypton-85, is even more problematical. In order to encounter a pocket of krypton-85, first the package must fail and then the escaping krypton-85 must be held in an area of noninterconnected porosity. However, there is no basis at this time to eliminate consideration of encountering particulate or gaseous contamination. During the subsequent phases of retrieval equipment study, further work is needed to establish design basis conditions for the retrieval system.

3.3.2 Criticality

All systems for processing, transporting, handling, storage, retrieval, emplacement, and isolation of radioactive waste will be designed to ensure that a nuclear criticality accident is not possible unless at least two unlikely, independent, and concurrent or sequential changes have occurred in the conditions essential to nuclear criticality safety. Each system will be designed for criticality safety under normal and accident conditions. The calculated effective multiplication factor (K_{eff}) must be sufficiently below unity to show at least a 5% margin, after allowance for the bias in the method of calculation and the uncertainty in the experiments used to validate the method of calculation.

The most certain method to ensure criticality safety is to design a vessel to be less than a minimum critical dimension. Spent fuel will typically retain about 1% enrichment, which implies a minimum critical cylinder diameter of 81 cm (32 in) for a container for optimally moderated, fully reflected, heterogeneous uranium oxide (Carter et al., 1968). This is larger than a waste package container's inside diameter, which is about 65 cm (26 in). Thus, the typically received fuel will be geometrically safe. On some occasions, fuel with less than normal burnup may be received. Enrichments as high as 4% are possible. This results in a minimum critical cylinder diameter of 25 cm (10 in), which is smaller than the waste package container. If high burnup and low enrichment are not to be license conditions of the plant, some other method of ensuring criticality control must be considered.

An acceptable method of criticality control is administrative control, if the packages cannot be shown to be inherently geometrically safe. One administrative control method that is often used at nuclear facilities is to limit the amount of moderating material near the nuclear fuel. Moderators are materials that slow down high energy neutrons, thus increasing the likelihood of a sustaining chain reaction (criticality). Ordinary water is good moderating material. One way to limit the amount of water is to pack the fuel tightly to minimize voids for any water to enter. The consolidated fuel waste form consists of fuel pins that are packed into a canister. The packing fraction (the ratio of fuel volume to the total volume available), with consolidated spent fuel is high, so that with consolidated fuel there is insufficient volume to allow enough water inside the package to give optimum moderation. Using moderator control would cause packing fraction to become a license condition, which could cause operational constraints. Additionally, it may be difficult to reach a sufficiently tight packing to ensure that the package K_{eff} is less than 0.95 if it were filled with and surrounded by water (McNair and Gore, 1980).

The selection of how to demonstrate criticality control (for example, geometrically safe accounting for burnup or administrative control by accounting for undermoderation) has not been made. In either case, criticality control is not expected to be a key issue in retrieval, at least while operating underground. The chlorine in salt has a high thermal neutron absorption cross section. A mixture of low burnup fuel and brine even at optimum moderation has a k_∞ of less than one (Gore et al., 1981). However, due to the significant potential for harm that could result from an inadvertent criticality, the issue should never be taken lightly. Considerable planning and analysis will be required during retrieval operations to ensure that criticality is a very low probability event.

3.3.3 Accountability and Safeguards

During the retrieval operation there must be provisions to ensure the control of special nuclear material. This implies that the waste packages should be marked (for example, with a serial number on a tag of corrosion resistant material) and that the location of each package should be recorded on emplacement. The marking must remain readable throughout the expected retrieval period. The emplacement records must be accurate and well maintained so that should retrieval occur, the packages can be found and an accounting made of emplaced versus retrieved material. Accountability will require careful record keeping both during emplacement and retrieval.

4.0 RETRIEVAL APPROACHES

This chapter describes the operations needed to retrieve a waste package. The retrieval process is divided into unit operations, and the functional requirements for each unit operation are described. Then equipment available to accomplish these functions is discussed. Finally, the effect of issues peculiar to retrieval on the design and capability of existing equipment are presented.

4.1 REMINING

If the option of backfilling the rooms soon after emplacement is selected, the first step in retrieval is removing the backfill or mining new openings to provide access for retrieval equipment. The excavation method should be flexible and capable of providing a stable excavated opening. This will entail removal of loose scaly material, slabs, and both consolidated and unconsolidated backfill material. The remining may occur in the outline of the original drifts or may involve driving new drifts.

4.1.1 Functional Requirements

The functional requirements are

- Re-excavation of entries and rooms including removal of bulkheads and plugs
- Operation at elevated temperature with possible release of steam or radionuclides
- Handling and disposing of salt at elevated temperatures and with possible radioactive contamination.

4.1.2 Remining Equipment Characteristics

The following remining methods are reviewed in this section:

- Continuous mining machines
- Drill and blast mining
- Tunnel boring machines.

4.1.2.1 Continuous Single or Dual Boom Excavators (Roadheaders)

A continuous single or dual boom roadheader is a machine that provides a rotating cutting head on the end of a hydraulically controlled boom. The boom can be raised and lowered vertically and swung from side to side, which allows very flexible positioning of the cutting head. The mined material, "muck," is gathered by mechanical arms and a conveyor and moved to the rear of the machine. These excavators have the ability to mine salt in a wide variety of degrees of consolidation. Single boom roadheaders have seen extensive use in evaporite mines. Although some problems occur in mining hard strata such as anhydrite lenses, salt backfill is well within the capability of these machines. Roadheaders typically use transverse (ripper) cutting heads instead of milling (in-line auger) cutting heads. The transverse cutters give about 25 to 30% better productivity. The cutters are usually equipped with conical self-sharpening plumbob bits for evaporite mining. There are two fundamentally different boom designs, hard rock booms and soft rock booms. The hard rock boom design is best suited to potash mining because of vibration-free cutting and lower bit consumption and maintenance costs. Soft rock booms may be applicable for salt, but the hard rock booms would be better, particularly in retrieval where operating conditions may be difficult.

Modification of existing equipment for retrieval conditions should be possible with existing technology. The critical area would probably be hydraulic systems. However, flame retardant hydraulic fluids are available, and low pressure hydraulic systems (e.g., below 10.3 to 13.8 MPa [1,500 to 2,000 psi]) can be used. The lower pressure systems are more reliable, require less filtration, and are less susceptible to contamination.

The roadheader can be mounted on a wheeled or a tracked chassis. A tracked crawler chassis offers the advantages of low ground pressure, which will allow it to work on soft surfaces such as a muckpile or poorly consolidated backfill (Kogelmann, 1983).

4.1.2.2 Drill and Blast Mining

Drill and blast is a classic mining method. Drilling machines drill a pattern of holes into a rock face, and the holes are filled with a blasting charge that is set off. The resulting muck then must be picked up and hauled away before the drill and blast sequence can be repeated. As well as providing a flexible mining method, the drill and blast method minimizes the risk from gas entrapped in the formation, because the drill holes provide a path for gas to be bled from the formation.

However, the drill and blast method may not be suitable for mining poorly consolidated backfill. Drilling and charge emplacement can be difficult in weak materials due to sloughing of the hole. Blasting may be ineffective in poorly consolidated material. Blasting also induces fracturing, which causes possible ground control problems. This could be a particular problem on retrieval where creep closure of the room could have induced instabilities in the salt mass prior to remining. There would also be considerable concern about blasting in the vicinity of waste packages when the physical condition of those packages is not known.

4.1.2.3 Tunnel Boring Machines

A tunnel boring machine is a driver with a full-face rotating head that has rock cutting bits mounted on it. The head is pushed into the rock mass by large, thrusting cylinders. Circular drifts of large diameter, up to 10 m (33 ft) or more, can be mined with machines of this type.

While a tunnel boring machine efficiently produces a relatively stable opening, it may lack the flexibility needed to remine drifts for waste retrieval.

4.1.3 Remining Issues

The following remining issues are discussed in this section:

- Gas outbursts
- Thermal environment
- Room stability.

4.1.3.1 Gas Outbursts

Some air will remain in a drift when it is backfilled. There is some concern that air-filled voids would be pressurized as consolidation occurs, resulting in the potential for gas outbursts during remining. Preliminary indications are that the backfill would not fully consolidate in the first 25 or more years (Wagner, 1980a and b). This would allow interconnected porosity that would permit the air to escape as creep closure occurs. As a result, large volumes of high pressure gas are not expected on a routine basis. There is, however, no way to ensure that isolated cases of air compression will not occur. Therefore the issue must be considered until it can be eliminated on a firm technical basis. Also, pressurized brine pockets at temperatures above 100°C (212°F) could be encountered and cause the evolution of steam.

The remining equipment must be designed to operate and protect the personnel from gas outbursts. This could involve modification of existing equipment to include operator protection features or development of remote control mining equipment.

A drill and blast method would probably be the easiest to adapt to trapped air conditions, as mentioned above. However, a continuous miner would probably be a more acceptable type of mining machine for retrieval remining. Continuous miners have been operated by remote control in mining situations.

4.1.3.2 Thermal Environment

Current generation mining equipment will not require extensive modification to operate at the temperatures expected to be present during retrieval. Loss of worker efficiency in a high temperature environment will be more limiting than equipment performance. Some areas of equipment design will, however, require special attention. Examples of such areas are

- Special cooling for internal combustion engines
- Temperature resistant lubricants and elastomers
- Special cutting bits.

4.1.3.3 Room Stability

The state of rooms after remining may be a concern because wall slabbing and decoupling of bedded strata may occur as rooms close. These problems may develop more rapidly at high temperatures because creep rates are faster. Also, if large numbers of packages are to be removed, maintaining access to rooms and keeping them open for the required period of time may be difficult, particularly if site integrity must be maintained.

It seems likely that support practices used in mining, such as rockbolting, will have limited success in improving the condition of openings, especially in hot salt. Built-up framework (cribs) may be usable to provide local support as needed. Probably, the proper design of underground layouts will be the most effective factor in controlling room stability problems.

4.2 PACKAGE LOCATION

During the retrieval operation, some effort will be required to locate the emplacement drifts and the waste packages and to determine the package orientation. The drifts may be backfilled, or significant creep closure may have occurred. Thus, some method must be available to locate the area to be mined. Heat generating nuclear waste packages in a salt repository may tend to shift due to buoyant forces and salt creep. Calculations have been performed that indicate some package movement may occur (Dawson and Tillerson, 1977). However, with the potential for the waste package to change position, some provision must be made for determining its location and orientation.

4.2.1 Functional Requirements

The functional requirements are

- Locate emplacement site (long range location of groups of packages
- Determine the precise location and orientation of the emplaced disposal package, e.g., tilt, shift.

4.2.2 Package Location Equipment Characteristics

The characteristics of the following types of package location equipment are described in this section:

- Radar
- Sonar
- Surveying
- Mechanical methods
- Geophysical measurements.

4.2.2.1 Radar

Electromagnetic radiation has been used in locating geologic features in coal (Coon et al., 1981) and salt (Unterberger, 1979). In these systems, electromagnetic radiation is beamed into a formation, and the reflected signals are detected. The magnitude of the return signal and the delay between transmission and return can be used to locate objects. Tests in salt indicate that a range of frequencies from 4,300 MHz to 230 MHz can be used to locate faults, interbeds, and brine pockets in salt. The high frequencies give high resolution and short ranges. Objects as small as 1 cm (0.4 in) or less can be located at distances up to 20 m (65 ft). High frequency systems have low power requirements and can be portable battery operated equipment. The 230 MHz system has resolution in the vicinity of 20 cm (8 in) and a range of over 400 m (1,312 ft). Power requirements for the low frequency are high enough that a small diesel generator or site power connection would probably be required.

There is no reason to expect that radar would be unable to locate a steel package in salt. There is a large difference in the electric permittivity and magnetic permeability of salt and iron. It is a change in these factors that causes the radar wave to be reflected and the reflecting object detected.

There are three areas of concern for application of radar to package location. First is the question of the accuracy of the location. A small object may reflect the radar beam and thus be detected. The size of the object that can be "seen" is inversely related to frequency and is the resolution as discussed above. Determination of distance depends on knowing the speed of electromagnetic radiation in the medium and on measuring the very short time delay between sending and receiving a signal. Thus, how accurately a location can be found depends on the quality of the electronics, homogeneity of the salt, and the care taken in the measurement of the speed of electromagnetic radiation in salt. Second, the existing radar systems require a large amount of operator skill to interpret the output. The output is essentially a collection of dots or lines that the operator must convert into a location of some geologic feature. This obviously requires a good bit of "art" on the part of the operator. Third, the salt must be quite dry, less than 0.1% moisture, for radar to operate with optimum range and resolution. Very low frequency systems, 30 MHz, can operate in salt with up to 1% water, but range is reduced and resolution is limited. This requirement may not be met in the vicinity of the package due to brine migration.

4.2.2.2 Sonar

Sonar has been used to probe salt in a manner much like that of radar (Unterberger, 1979). Sonar uses sound waves that are reflected from density discontinuities to locate geologic features in a manner analogous to the use of electromagnetic waves in radar systems. A sonar system using a 24 kHz frequency sound wave can probe about 400 m (1,312 ft) into dry salt or about 150 m (492 ft) into wet salt. Resolution is on the order of several centimeters.

Radar generally has advantages over sonar. The resolution and range are better for radar as long as the moisture content is low. Also, there is no coupling problem with radar. Radar waves will propagate past the air-salt interface with less than 20% of the energy lost by reflection. This is not the case with sound waves. The sonar wave generator must be coupled to a smooth salt surface with a coupling fluid such as glycerin. However, the concerns with absolute accuracy and signal interpretation discussed in the radar section also apply to sonar.

Sonar's main advantage is the ability to operate in wet salt. It can also be used to supplement radar systems.

4.2.2.3 Surveying

Establishing a fixed reference point as a starting point for surveying is a well-proven technology. Such a reference point would then allow the determination of where the original drifts were and where the packages had been placed.

This method has the advantage of needing only very simple equipment. It does not allow, however, any determination of where a package may have moved to as a result of salt creep. In this case, the assumption is made that any shift will be of the repository as a whole. Individual package movements probably could not be detected.

4.2.2.4 Mechanical Methods

Simple and direct mechanical methods are available for package location. A concrete plug may be used to allow positive location by the mining machine. It would also be possible to attach a cable to aid in location and retrieval of the cask. The technology is available to mark the backfill with a distinctive color or to utilize the radiation-induced color change. It would be possible to use different colors for different areas of backfill. For example, the salt that is put into the emplacement opening could be a different color from the salt used for drift backfill.

This method is simple and gives positive indication of location. However, it does not allow the detection of actual package location at a distance. Salt creep or brine migration may also result in movement of the colored salt, which could reduce the precision of this method.

4.2.2.5 Geophysical Measurements

Finally, use of geophysical measurements such as gravity or magnetic detectors is also within current technology. These methods would allow location of the package centerline with a low but usable accuracy and resolution when working in a drift a few meters from the package.

4.2.3 Package Location Equipment Issues

A variety of methods are available for locating packages. Selection of the method depends upon

1. The nature of the site: for example, radar location systems have limited range in salt with high moisture content.

2. The degree of precision and range required: for example, high frequency radar is capable of high resolution but is limited in range. Lower frequency radar and sonar have reduced resolution and greater range.

Package location operations will probably require a variety of techniques used in sequence or conjunction to allow a retrieval process to home in on a package. Mechanical means, such as surveying from a fixed marker or mining along previously placed colored backfill, will allow the general position of emplacement drifts to be established. Then sonar or lower frequency radar would give package locations. Exact package orientation could be established with high frequency radar, once the vicinity of the package had been reached.

There is no reason to expect that package location methods will be beyond the state of the art. Even with very wet salt it should be possible to locate a package, although the exact orientation might be difficult to determine, and the retrieval equipment would need to allow for less accurate knowledge of package position. In dry salt, it should be possible to determine the location and orientation of the package within a few centimeters.

Areas that still require development are

- Developing functional requirements
- Testing radar and sonar system capabilities such as range, resolution, and accuracy in wet and dry salt with steel objects
- Testing gravity and magnetic methods under these conditions to determine range, resolution, and accuracy
- Developing techniques of using various location systems for finding a package in salt in concert with each other
- Developing a good human-machine interface that gives an unambiguous readout of package position with a minimum need for interpretation by the operator.

4.3 PACKAGE REMOVAL PREPARATION

Having determined in general where packages are located, driven a drift to the area, and found the package orientation, the package must then be freed from the surrounding material and prepared for lifting. Depending on the mode of emplacement, this could involve removal of a vertical or horizontal package either from the salt or from a sleeve. The package may be removed with some surrounding salt, with container and canister only, or with the container left behind and only the canister being removed.

4.3.1 Functional Requirements

The functional requirements are

- Free package from surrounding medium
- Prepare package to be moved from the emplacement location.

4.3.2 Package Removal Preparation Equipment Characteristics

The characteristics of the following types of package removal equipment are discussed in this section:

- Overcore drilling
- Slab cutting
- Container cutting
- Hydraulic trepanning
- Sand blasting.

4.3.2.1 Overcore Drilling

One method of freeing the package and preparing to move it into the drift is overcoring. In this operation, a slot is cut around the package to form a salt core. The core (package and surrounding salt) can then be broken off and latched by a fixture for moving it into the drift. This method is applicable primarily to packages emplaced vertically or horizontally in an unlined borehole.

Core cutting barrels in the range of 1.8 m (6 ft) in diameter and 1.8 m (6 ft) in length have been used in practice for cutting core samples during dam construction and shaft sinking. They typically require 40 to 100 hp drive motors (Stack, 1982). Due to the low demand, they are not routinely available but can be built on special order. The barrel can be fitted with tungsten carbide insert cutters for soft rock or roller bit cutters for hard rock.

Longer core cutters required to overcore a waste package, up to about 6 m (20 ft) long, should not present any major challenge to the technology. The barrel would need to be in sections to reduce overhead clearance requirements. Removal of the cuttings could create some complication but should not be a major difficulty. It should be possible to remove cuttings by pneumatic conveying.

In most cases the large diameter core cutting equipment uses a separate device to break the core free and lift it. A core lifting fixture could break the core loose by driving wedges between it and the shaft wall or by detonating small explosive charges without endangering the operator or damaging the package. The view has been expressed by core drill operators that a core could be broken free by pulling or rotating the lifter without the use of wedges or explosive charges.

Large diameter drilling barrels may be fitted with integral core lifters. Using a combined core cutter and lifter would cause an increase in the complexity of the machine but would reduce the number of steps involved in retrieval.

Overcoring has several attractive features, assuming that the core can be kept intact. Salt that is in contact with the package would not be disturbed. Thus, in the event of a breached package, there is less possibility of encountering contaminated salt, so less contaminated dust should be produced. Additionally, the encasing salt would give some degree of containment and shielding. Lifting the core also avoids depending upon the lifting fixture on the container and making assumptions about container condition.

It has yet to be demonstrated that a core consisting of a thin layer of salt over a heavy steel container can be lifted intact. Radiation effects, vibration, and stress relief may cause the salt layer to lose strength, and the strength of the salt may not be sufficient to avoid having the salt layer break up when it is lifted. This is a major question about the overcoring method.

4.3.2.2 Slab Cutting

The package could be cut free and prepared for moving by cutting out a slab of salt. This operation would be much like core cutting except that a cutter bar would be used to cut out a rectangular slot around a waste package. The block would then be broken off to form a parallelepiped of salt containing a waste package. This method would be applicable mainly to vertical or horizontal emplacement without a borehole liner.

A cutter bar is a metal plate or jib with a chain of cutting teeth that runs along the edge of the jib much like a large chain saw. The jib can be mounted on a vehicle for mobility. It can be rotated so that the cutting teeth are horizontal (to cut into a wall) or vertical (to cut into the floor). The bar is traversed and/or pivoted for cutting. Drive motors for the cutting chain are on the order of 40 to 100 hp (Stack, 1982). Bars for cutting salt have been made up to 7.6 m (25 ft) long, but 5 m (16 ft) is a more typical maximum length. The cutter bar can operate to depths up to its own bar length. The cut can be made using arc cutting, with less opening height or width than the bar length. Thus, cutting can be done without the sectional approach that is a problem with core cutting. However, the operation requires several cuts, which would slow the operation. Otherwise, slab cutting has similar advantages and disadvantages to core cutting. The primary question is keeping the salt around the package intact during cutting and handling.

4.3.2.3 Container Cutting

In this method the container, either the liner in the case of a lined borehole or the outer thick walled container of the waste package in the unlined case, would be intentionally breached. Only the contents would be removed, and the container would be left in the salt. To prepare the package for retrieval in this manner, the following steps would be required. The salt over the package would be mined with coring equipment or by drilling to expose the top of the container or hole liner. Once the top was exposed, the closure would be cut out and removed. This would allow access to the canister or, in the lined borehole case, the package.

Equipment exists to accomplish the removal of the salt. Some care would be needed when the mining reached the top of the package. However, since the top is to be removed it could be allowed to sustain some damage as long as it was not breached unexpectedly.

The advantage of this method is that it allows retrieval of a package that has not been exposed to the salt environment. Thus, there is less concern about the condition of the lifting fixture and no need to break the package free from the salt.

The disadvantage in the unlined case is that the bare canister must be handled, and it has very high radiation dose rates. Also, in the case of a leaking container, the surface contamination levels could be very high. This would also raise questions as to the integrity of the canister and the ability to handle it. Due to the inherent difficulties of operating underground, the design and operation of remote control equipment will be challenging.

These problems may be solved if a borehole liner is used so that the package (both canister and container) could be removed. The lined concept could add some expense and complication to the repository design, however.

4.3.2.4 Hydraulic Trepanning

In this retrieval system the salt surrounding the package would be dissolved to free the package. Holes would be drilled around the package and then be filled with water to dissolve the salt and form a brine pocket. The package would then be latched by a reach rod for lifting from the brine. This method could be used to retrieve both horizontal and vertical packages.

The hydraulic trepanning approach has the advantage of being both mechanically and conceptually simple. However, it presents some practical problems. The subsequent package handling step would be complicated by being required to be performed over a brine bog of uncertain extent, and the fact that the package would be coated with potentially contaminated brine.

The use of water could accelerate package corrosion and compromise the long-term stability of the repository. With a leaking container, significant volumes of radioactive waste would be generated, and it would be difficult to control the spread of contamination. However, the method may appear more controversial than it actually is. It may be possible to demonstrate it to be workable.

4.3.2.5 Sand Blasting

In this option, conventional mining techniques could be used to reach the vicinity of the package. Then salt would be sand blasted away to free the package to allow it to be moved. With this method, as with solution mining, the concept is very simple. It avoids the potential degradation of package and repository that might arise from using water. However, with a leaking package, radioactive wastes would be generated and contamination spread, and airborne activity levels would be difficult to control.

4.3.3 Package Removal Preparation Equipment Issues

The following package removal issues are discussed in this section:

- Thermal effects
- Radiation effects.

4.3.3.1 Thermal Effects

The salt temperatures encountered in this phase will be higher than those encountered in the remining phase and will also necessitate a high degree of environmental control for operator protection.

4.3.3.2 Radiation Effects

As the package is reached, the potential for radiological hazard increases. Less shielding is provided as salt is removed, so direct radiation could become significant. In the unlikely event that a package has leaked, the potential for encountering contaminated salt or gaseous radioactivity is greater. Comprehensive systems for operator protection will be needed during this phase.

4.4 PACKAGE HANDLING

Once the package has been cut loose from the surrounding environment, it must be moved from the emplacement location into the drift and transferred to the surface. This study will ignore the hoisting, surface handling, and ultimate disposition of the package.

4.4.1 Functional Requirements

The functional requirements are

- Move the package from the emplacement location
- Transport the package through the drifts to the hoist location.

4.4.2 Package Handling Equipment Characteristics

Although heavy loads are frequently handled in mines, there is limited experience with grappling, lifting, and handling a large, heavy, radioactive source in a mine. It is assumed that the waste emplacement transporter or a similar type of vehicle can be used for moving a package during retrieval as it did during emplacement. Major modifications for operating in a high temperature, potentially contaminated environment will be needed.

Project Salt Vault used a rubber-tired vehicle to transport waste canisters (Bradshaw and McClain, 1971). The trailer had a mass of 36,400 kg (80,247 lb) including a 23,000 kg (50,705 lb) shield. The shield vessel has a slide valve at the top to receive a canister and a second valve at the bottom to allow it to be lowered into the emplacement hole. The vehicle positions the cask within a 0.9-m (3-ft) square. Hydraulic drives provide displacement along three axes to locate the cask over the hole with an accuracy of $\pm$0.16 cm (0.06 in). It was capable of turning in 7.6-m- (25-ft-) wide corridors. The canisters were 12.7 cm (5 in) in diameter and 229 cm (90 in) long.

Testing operations at the Asse mine used a rubber-tired truck to carry a transfer shield containing cobalt-60 test sources (Rothfuchs et al., 1986). The shield has a mass of 10,000 kg (22,046 lb). The shield used a single slide valve for loading and unloading. The shield is transported on a special low bed truck and is offloaded and positioned with a fork lift. The cobalt-60 canisters were 19.8 cm (8 in) in diameter and 99.5 cm (39 in) long. They contained 9,430 Ci of cobalt-60.

Spent fuel storage testing operations at the Nevada test site included underground transport of a waste capsule with a rail-based system (Duncan et al., 1980). The transfer cask weight was 45,000 kg (99,206 lb). It included two-piece sliding gates top and bottom to provide top loading and bottom unloading. The canister was 35.6 cm (14 in) in diameter and 427 cm (168 in) long.

4.5 ENVIRONMENTAL CONTROL

The retrieval operations will have to be carried out in very difficult conditions. The salt and air temperatures may be quite high, and the room stability may be poor. There is the potential for steam generation if pressurized brine pockets are opened and the brine flashes; there is the potential for high radiation fields and contamination. Provision must be made for control of this environment.

4.5.1 Functional Requirements

The functional requirements are

- Maintain worker safety
- Provide sufficient ventilation for personnel comfort and equipment operation
- Control contamination and airborne activity.

4.5.2 Environmental Control Issues

Several approaches are available for controlling the working environment. An attempt could be made to keep the drifts as a routine work area, sometimes called a Radiation Protection Zone III condition in nuclear facilities. Operating personnel would wear light anti-contamination clothing and carry respiratory gear immediately available for emergencies. This may require (1) blast cooling of the work area prior to entry, (2) very high airflows to control temperatures, and (3) removing radioactive gases and contamination. Additional cooling for workers can be supplied by vortex cooling nozzles or ice vests as needed. Temporary shielding and a transfer cask for the waste package could be used to control package radiation. At the other extreme, the working area could be declared strictly off limits, a Radiation Protection Zone I. All activities would be done by remote operation. A significant airflow would still probably be needed to control contamination and reduce temperatures. An intermediate concept would be to provide the operator with a shielded operating space with a controlled atmosphere, such as the equipment cab, or to allow remote operation by line of sight to provide some separation of the operator from the high hazard area.

All three methods have faults. The Zone III concept would require very large ventilation rates. Providing cooling and a heat sink for the waste heat would be difficult. It also provides limited protection in the event of unexpected conditions. Should a pocket of contamination be encountered or a waste package be inadvertently exposed by mining, overexposures would almost certainly occur before the miners could react.

The Zone I fully remote approach allows a high degree of protection but would be costly and challenges the state of the art for routine operation with a large number of packages. The shielded cab or line-of-sight methods may offer a reasonable compromise but are not obviously the best choices.

5.0 RECOMMENDATIONS

The earlier sections of this document are intended to summarize the current state of the retrieval issues. Chapter 2 reviews the programmatic and regulatory basis for retrieval and introduces the concept of a scenario-based approach for retrieval system analysis. Chapter 3 provides an overview of some broad issues involved in retrieval. Chapter 4 discusses the current capabilities of equipment and indicates some specific development needs.

The picture that emerges from the discussion in the preceding sections is that retrieval is a complex issue and that not all of the issues are fully resolved. Concentrated effort with cooperation among all participants is needed to fully resolve the retrieval issues. However, there is no indication that the goal of a proof-of-principle demonstration prior to license application is beyond current technology supplemented by a serious development program.

Several design features of the repository are not directly involved in retrieval but can have a major effect on the design of retrieval equipment and, in fact, on the ease of accomplishing retrieval. Included among these are

- Emplacement orientation
- Borehole design
- Areal power density (packages per unit area).

The emplacement orientation, horizontal or vertical, will have major implications on retrieval. Clearly the configuration of the equipment used will be profoundly influenced by waste package orientation. Additionally, the orientation will influence the size and shape of the rooms and thus their stability. This will affect the ease of remining and subsequent retrieval operations.

The task of retrieval can be made much easier if the borehole is designed to ensure that the package remains free. In principle, a very large annulus could be left in such a way that the borehole wall would not reach the package surface during the retrieval period. A second approach would be to provide a liner that is designed to last throughout the expected retrieval period.

A borehole liner would make removal of the package easier. It would also have other advantages for retrieval including

- Aiding in the location of packages
- Protecting the package during mining
- Providing additional shielding.

Reduced areal power density (emplacing fewer packages per unit area) would result in significantly lower temperatures in the repository. The lower temperatures would have a direct benefit by making remining and environmental control easier. There should also be less creep and less effect on salt strength, giving better room stability. The main disadvantage of this method is the need for increased repository area and thus more mining and higher costs.

In addition to the repository design features discussed above, specific equipment development and testing will be required. Some plan needs to be instituted to integrate repository design and retrievability needs, as well as to execute the necessary equipment development. Based on the work done in preparing this report, a preliminary plan was outlined. This proposed plan is illustrated in Figure 5-1. The elements of this plan are as follows:

1. Develop program plan: a plan that is consistent with existing networks and contract documents but that provides more detailed planning focused specifically on retrieval should be developed. This implementation plan should delineate the objectives and baseline assumptions that will control the concept development. The plan should consist of a definition of what is required to complete a proof-of-principle demonstration and license application design, an outline of the functional requirements of the retrieval process, and a preliminary description of the retrieval scenarios. Based on this framework, the plan should give detailed task descriptions of the steps to develop the data needed for the proof-of-principle demonstration and license application design and should establish the responsibility for completing the tasks. Major decision points and the organizations that must concur at these decision points should be identified. The schedule and budget for the effort should be scoped. This is an Office of Nuclear Waste Isolation (ONWI) responsibility.

2. Identify scenarios: several preliminary scenarios should be developed to serve as the initial framework for retrieval system development. The scenarios should be sufficiently detailed to allow a definition of the operating conditions that would be encountered during retrieval. Some factors that must be considered are

   - Rock and air temperatures
   - Radiation levels
   - Contamination potential
   - Container condition
   - Underground condition
   - Emplacement geometry.

   The scenarios must consider the concerns raised in the earlier sections. This does not mean that all of them would be strung together to form a scenario. In many cases it may be possible to show that a concern is not valid due to the physics of the situation or the design of the emplacement system and package. However, no concern should be eliminated without a sound, well-documented, scientific basis. This is an ONWI responsibility with Fluor Technology, Inc., input.

3. Develop block diagrams, functional specifications, and flow sheets: preliminary designs should be documented in simple block diagrams, functional specifications, and flow sheets. This task should develop the functional requirements for the retrieval operations. The block diagram would show each separate function in the overall system. Functional specifications and flow sheets should be

Activities / Responsible Organization	Develop Program Plan	Identify Scenarios	Develop Block Diagrams, Functional Specifica-tions, and Flow Sheets	Identify Major Areas for Study	Refine Scenarios	Perform Preliminary Concept Studies	Perform Preliminary Equipment Studies	Develop Specifica-tions for Testing	Equipment Tests	Select Equipment Concepts	Scope and Specify Retrieval Equipment	Integrate Equipment into Repository Design
ONWI	Lead	Lead	Review	Lead	Lead	Review	Review	Review	Review	Review	Review	Review
Fluor	Support	Support	Lead	Support	Support	Lead	Support	Lead	Support	Lead	Support	Lead
Package Vendor							Lead		Lead		Lead	

Proof-of-Principal Demonstration

License Application Design

Retrieval Equipment Development Responsibility Matrix

Figure 5-1

developed from the block diagrams. Factors that should be considered include

- Material types and quantities to be handled
- Operator protection requirements
- Equipment functional requirements.

This is a Fluor Technology, Inc., responsibility with ONWI review.

4. Identify major areas for study: the retrieval block diagrams should be analyzed in light of the scenarios. This would lead to identification of areas that require further study to allow refinement of the scenarios and performance of conceptual studies to narrow the selection of retrieval equipment designs. This is an ONWI responsibility with Fluor Technology, Inc., support.

5. Refine scenarios: the definition of the basic retrieval scenarios would be improved by the addition of greater detail, and more concrete demonstration that they are reasonable and that they bound the worst case conditions. This is an ONWI responsibility with Fluor Technology, Inc., support.

6. Preliminary concept studies: concepts should be evaluated and refined to define the information needed to complete a proof-of-principle demonstration and license application design for retrieval equipment. Many of the machines and mechanical devices that are required for waste emplacement/retrieval can be specified so that existing devices or slight modifications of them can be purchased off the shelf; such equipment should be designated. Other devices and fixtures will need design and development. These should be flagged for development by the package vendor. This is a Fluor Technology, Inc., responsibility with ONWI support.

7. Preliminary equipment studies: preliminary equipment analysis should be performed to define the information needed to support equipment development for a proof-of-principle demonstration and license application design. This is a responsibility of the package vendor.

8. Develop specifications for testing: specifications for equipment development and testing needed to complete proof-of-principle demonstration and license application design should be written. This is a Fluor Technology, Inc., responsibility with ONWI review.

9. Equipment tests: testing and development of equipment should be done to allow selection of concepts for retrieval equipment and design of the equipment. Testing would include design, specification, purchase, and testing to ensure that sufficient information is available to design and specify the equipment identified for development in Item 6. This testing will complete the proof-of-principle demonstration. This is a responsibility of the package vendor with support from Fluor Technology, Inc., and review by ONWI.

10. Select equipment concepts: final equipment concepts should be chosen. This is a Fluor Technology, Inc., responsibility with ONWI review.

11. Scope equipment: complete test reports that describe the retrieval equipment test results should be written. This is a responsibility of the package vendor.

12. Integrate equipment into repository design: retrieval equipment should be specified and integrated into the repository design. This effort should complete license application design for retrieval equipment. This is a Fluor Technology, Inc., responsibility with support from the package vendor and review by ONWI.

6.0 CONCLUSION

Retrieval is an event that, although it is not expected, must be planned for. Both high-level programmatic documents and Federal regulations require that the waste should be retrievable. It is therefore an important design consideration that the option exists to retrieve waste in the unlikely event that it is needed.

There are several broad issues involved in a repository in salt that have significant implications to retrieval systems. Among these are high temperatures, which can affect mining equipment operation and personnel safety; the viscoplastic behavior of salt that results in room closure and increased potential for unstable openings; and nuclear issues such as radiation and contamination, criticality, and accountability and safeguards.

There are also many design features of the repository that can influence retrieval. These include emplacement orientation (horizontal or vertical), borehole design (lined or unlined), and areal power density (packages per unit area).

The issue of retrieval is complex now and likely to remain so. Further definition of the issues and development of technology needs to be completed before all open issues can be closed. However, there is no indication that the development of retrieval capability is impossible within the framework of existing equipment and a reasonable development effort. Many of the techniques that can be applied to retrieval such as remote operation or radar probing of geologic formations have been done in a mine environment.

An implementation plan for retrieval development should be created. This plan should clearly define the issues involved in retrieval and the objectives of the development effort. It should specify the work needed to reach these objectives, the key decision points, the groups responsible for the work, and how the effort is to be coordinated. A preliminary outline of task description for such a plan has been developed.

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